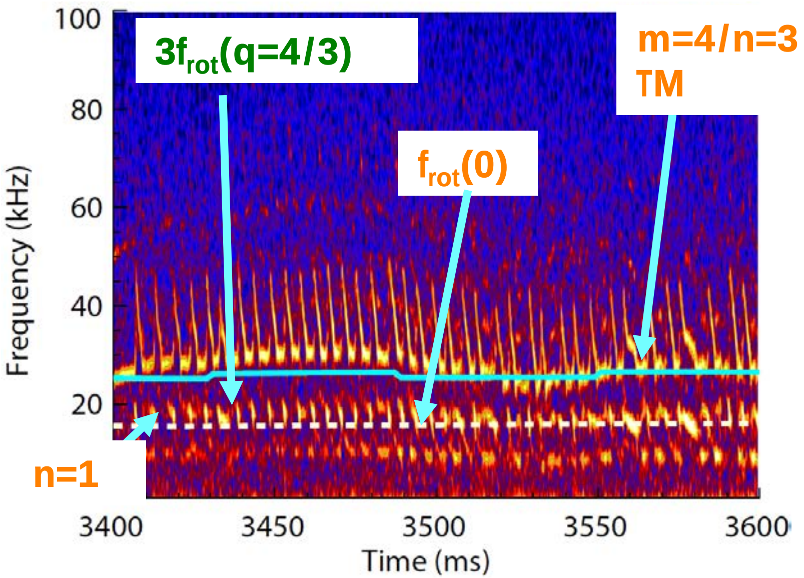
Cause and Impact of Low-Frequency Chirping Modes in DIII-D Hybrid Discharges

By **D. Liu[1], ,** W.W. Heidbrink[1], M. Podesta[2], Z.Z. Ren[3], G.Y. Fu[4]
C.C. Petty[5], F. Turco[6] and M. A. Van Zeeland[5]

[1]*University of California, Irvine*
[2]*Princeton Plasma Physics Laboratory*
[3]*Dalian University of Technology*
[4]*Zhejiang University*
[5]*General Atomic*
[6]*Columbia University*



16th Technical Meeting on Energetic Particles in Magnetic Confinement Systems – Theory of Plasma Instabilities

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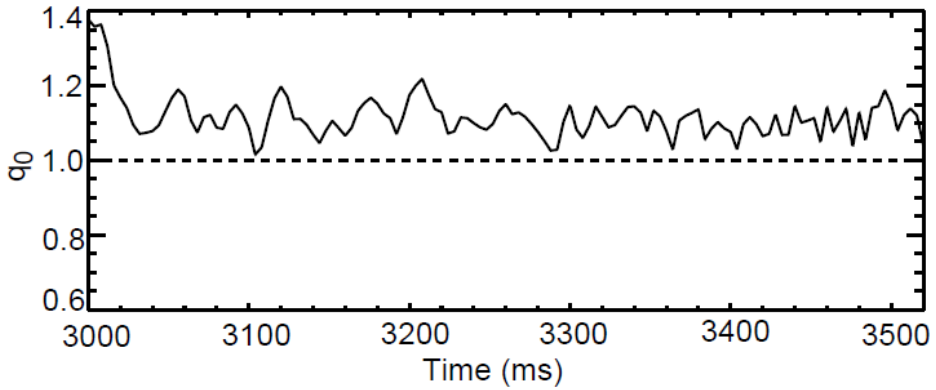
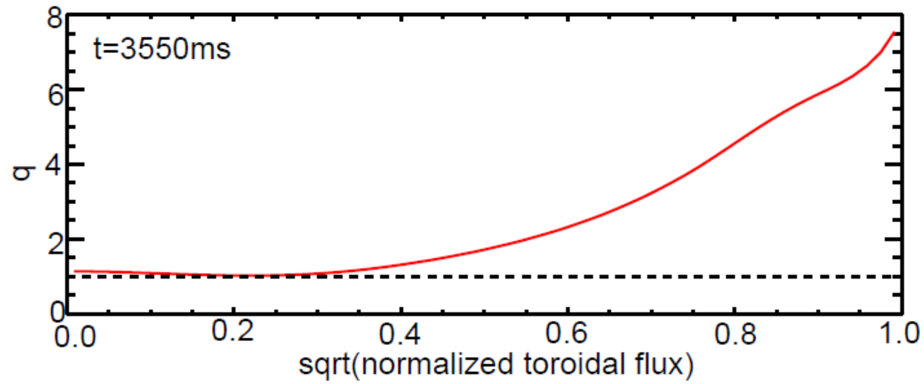
UCI University of California, Irvine

Significant Variations of Fast-ion Instabilities Observed in Hybrid Discharges with Electron Cyclotron (EC) Waves





- **Hybrid: long duration, high performance & steady H-mode; viable scenario for ITER operation**
  - Steady tearing mode (TM) often present; modest reduction in particle and energy confinement
  - low magnetic shear in the core with q_0 close to unity

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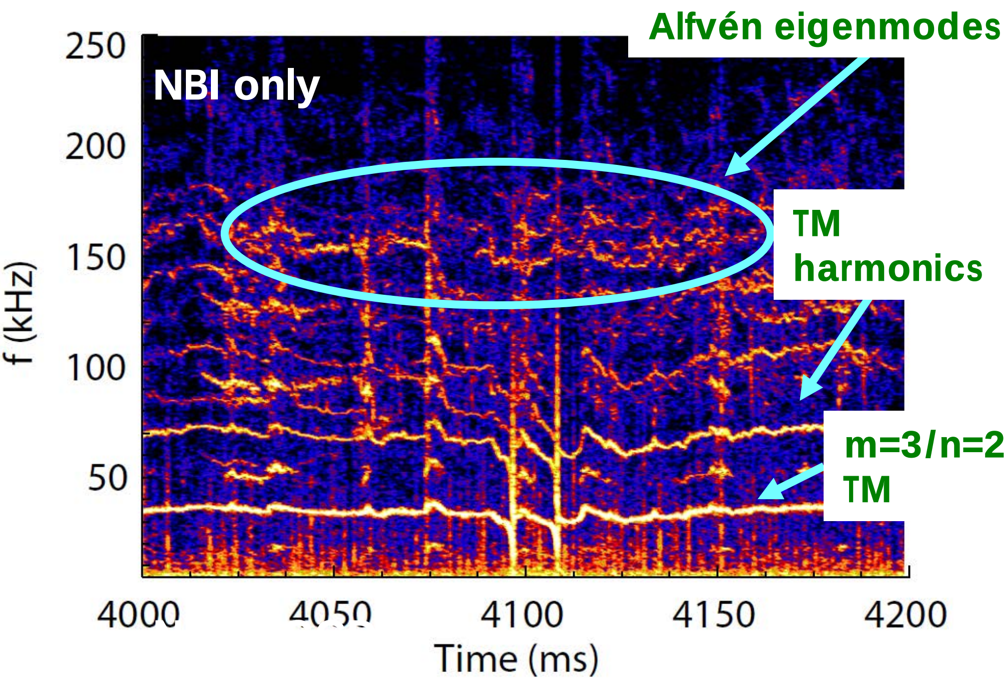

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  - AEs could be TAE/EAE/BAE
  - D_f of 1.0-2.0m^2/s needed to match classical neutron rate

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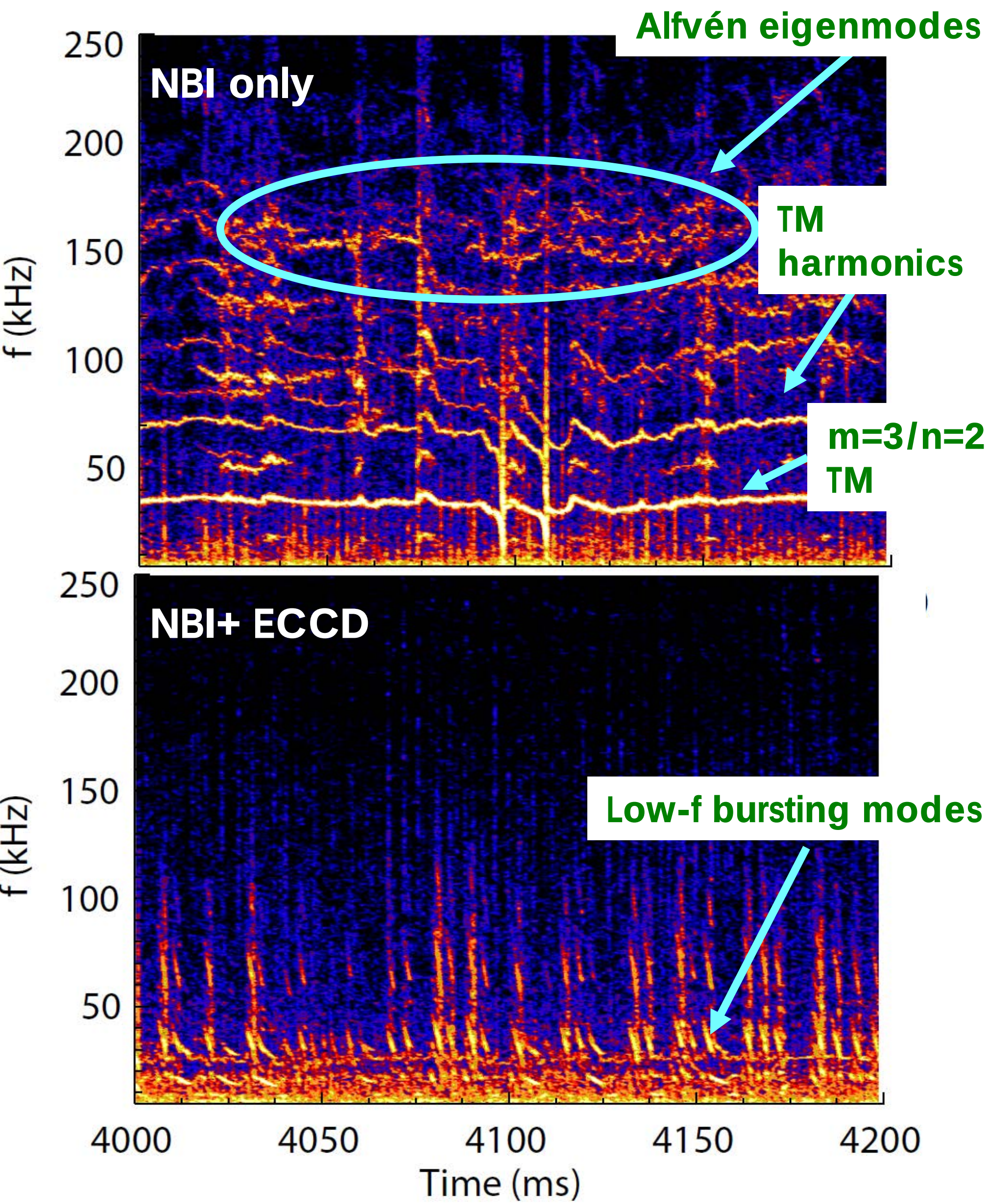

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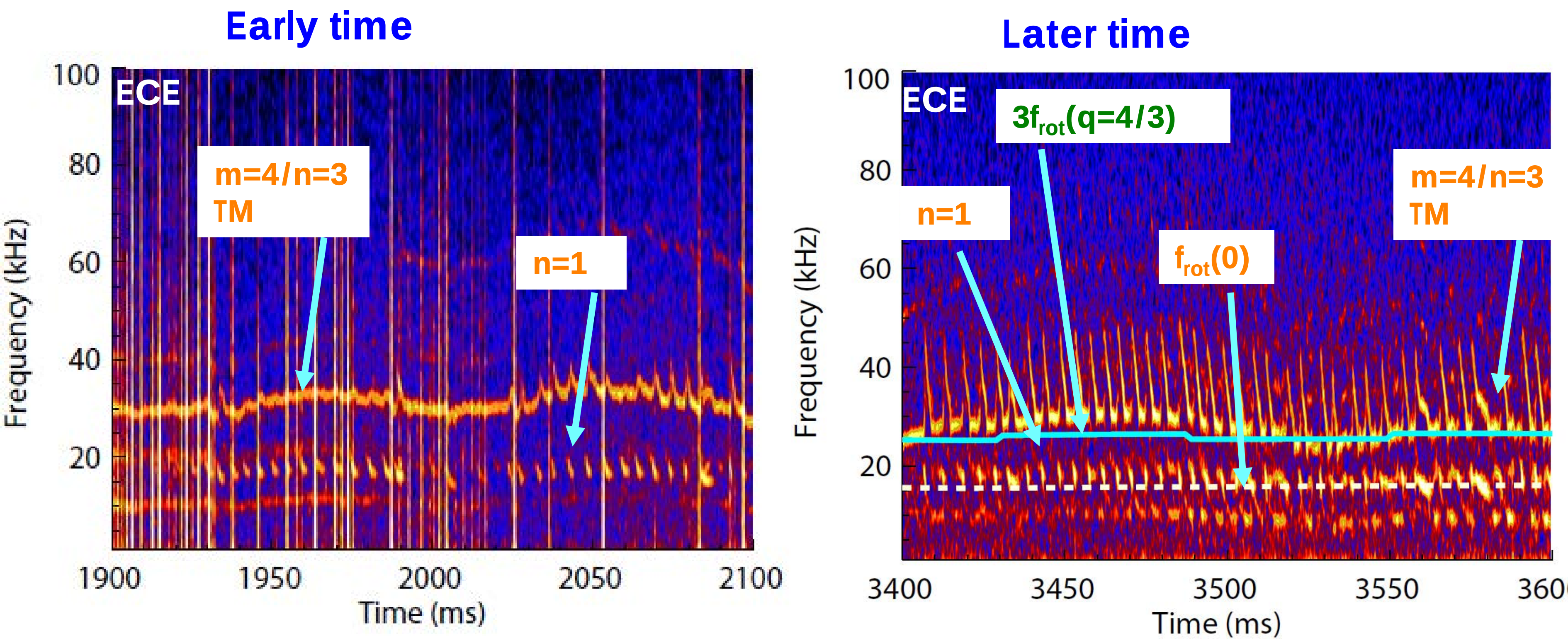
  - AEs could be TAE/EAE/BAE
  - D_f of 1.0-2.0m^2/s needed to match classical neutron rate
- **With NBI and EC, AE activity often became weaker/suppressed; low-f bursting modes appear.**
  - D_f of 0.5-1.0m^2/s needed to match classical neutron rate

Outline

- **Experimental observations and database study**
  - With NBI + EC, AE → low-f bursting modes
  - low-f bursting modes are usually chirping TM; occasionally fishbones
- **Hypotheses and modelling for the instability transition**
  - Large (trapped) fast-ion population responsible for the transition
- **Impact and plausible reasons for low-f bursting modes**
  - Fast ion losses observed only when n=1 mode is large
  - TM & fishbones interplay through fast-ion channeling in phase space
- **Summary and future work**

Goal: understand fast-ion instabilities in hybrids & their interaction with TM to improve the plasma performance

Low-Frequency Bursting Mode can be Chirping Tearing Mode (TM) or Fishbones



- NBI starts at 1500ms, EC starts at t=1700ms, steady TM at 1725ms
- Fishbones appear at t=1750ms, co-exist with steady TM
- t>2025ms, TM frequency abruptly jumps up and then chirps down within 1ms
- Note: n=1 mode can be very weak, sometimes only visible in magnetics

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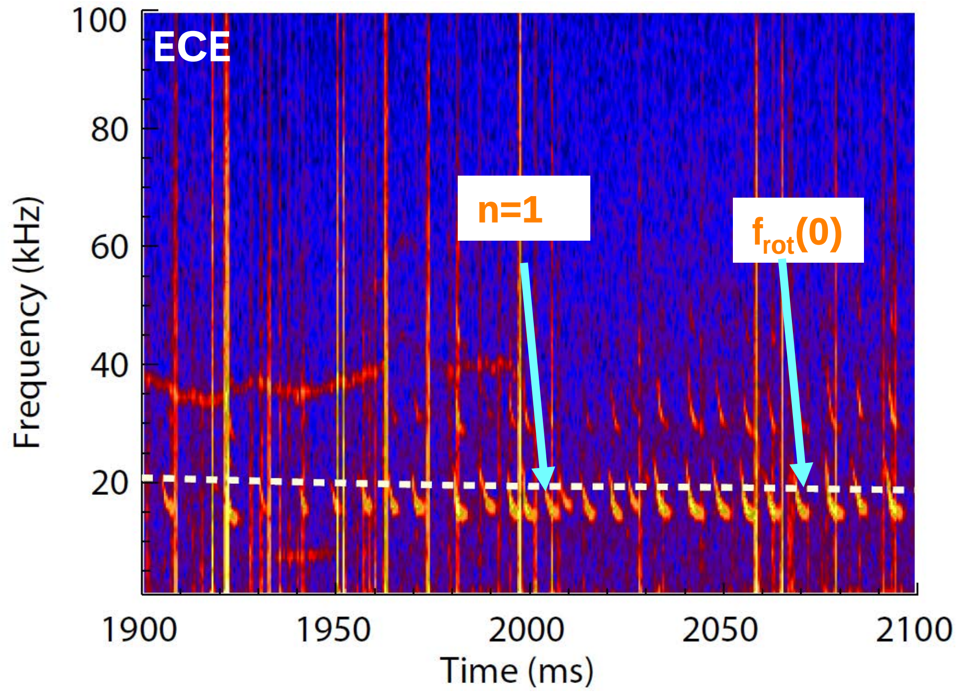
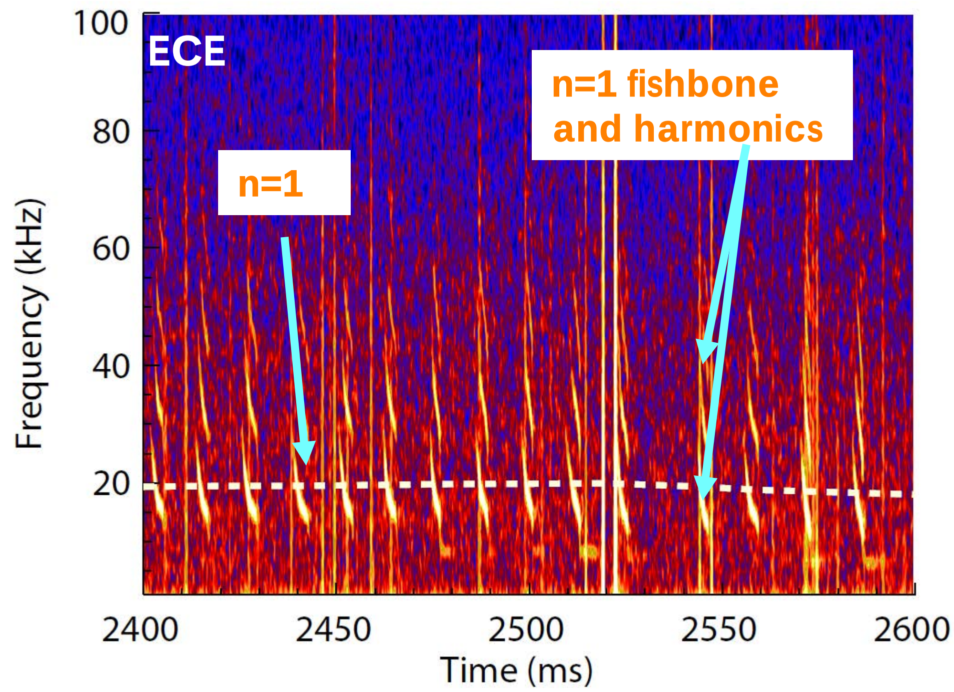
Low-Frequency Bursting Mode can be Chirping TM or Fishbones (Cont'd)

Early time



Later time



- TM and fishbones co-exist at the beginning, and then TM is suppressed (at t=1960ms). Harmonics of n=1 start to appear.
- Relatively rare in the database (3 shots only)

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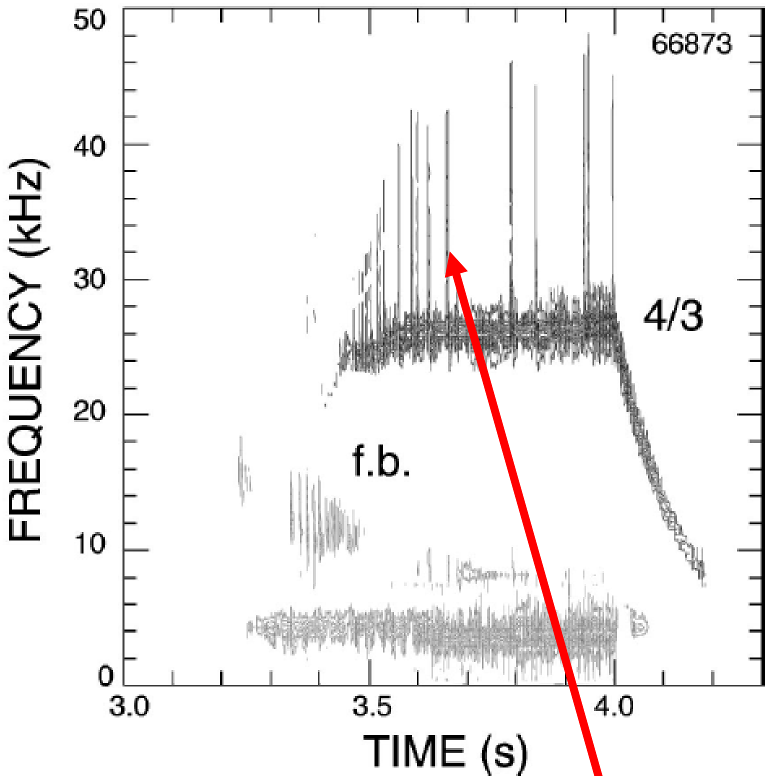
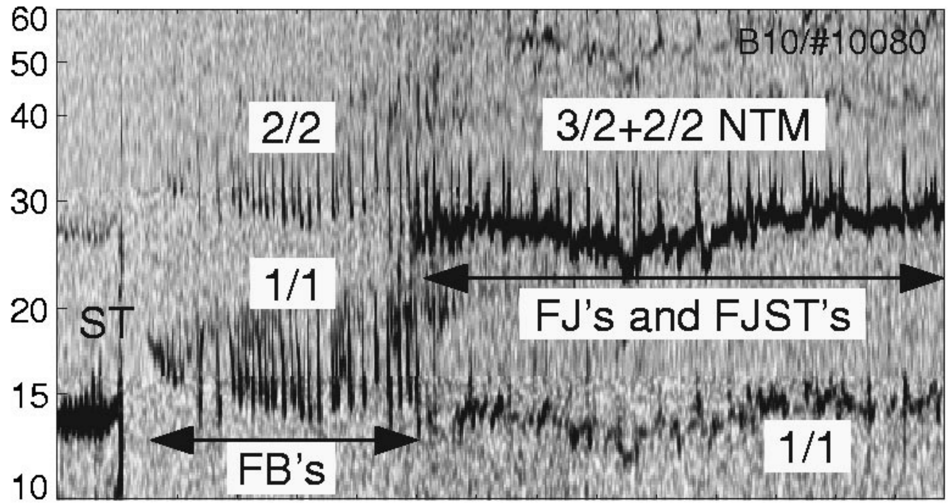
Chirping TM has been Observed on Other Facilities but not well Understood

TFTR *E. D. Fredrickson POP 2002*



S. Gunter NF 1999, Sesnic POP 2000



ASDEX-Upgrade

- TFTR: NTM frequency jumps up and chirps down

- ASDEX: Fishbones initiate NTM. Frequency jumps up and chirps down with a typical repetition frequency of fishbone
- Chirping TM was also observed in HL-2A (*Chen NF 2019*), EAST(*Li PPCF 2016*)

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A Database is Built to Study the Cause of Variation of Instabilities in Hybrid Plasmas

- **Summary of observations**
- **AEs**: in NBI-only or early phase of NBI+EC discharges
- **Low-f bursting modes**: 200-300 ms after EC; rare in low torque hybrids with counter-NBI or high-density hybrids.

- **The database include**
- 4-5 time slices per shot, totally 40 hybrid shots
- Flags for steady TM, chirping TM, fishbone, AE, ELM
- P_{NBI}, $P_{EC,}$ q profile from efit02 with E_r correction
- Plasma/fast-ion pressure and beta, fast ion density … are extracted from TRANSP runs that assume classical fast ion behavior

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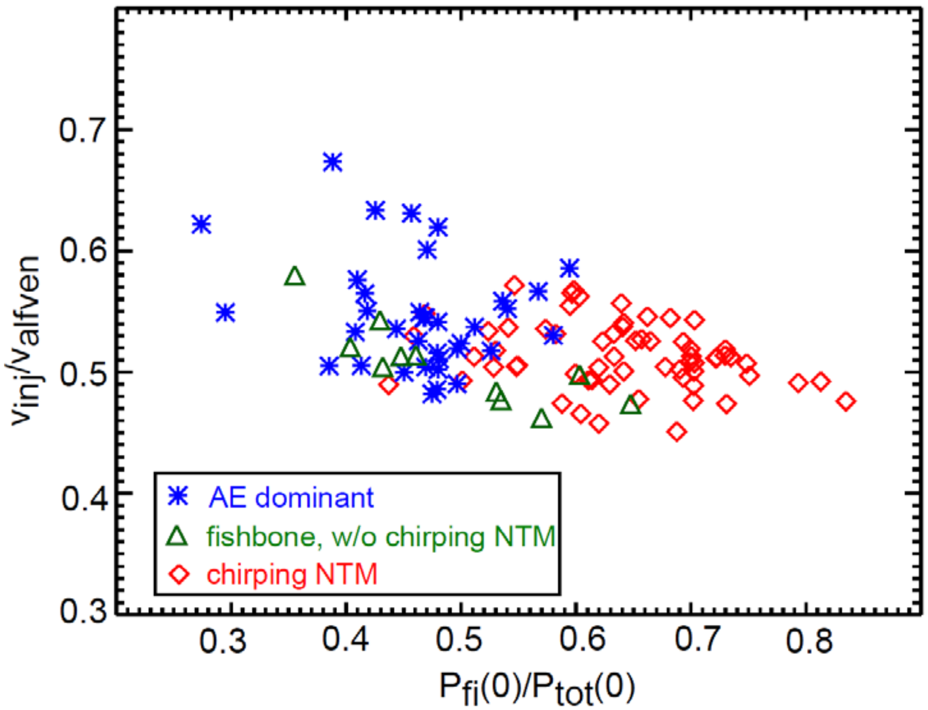
The Database Suggests that Occurrence of Low-Frequency Bursting Mode is Mainly due to Large Fast Ion Population



- AE: $P_{fi}(0)/P_{tot}(0)$~ 0.3-0.5 and v_{inj}/v_{alfven}>0.6
- Low-frequency bursting modes: $P_{fi}(0)/P_{tot}(0)$>0.5 and v_{inj}/v_{alfven} <0.6. Pure fishbones (w/o chirping NTM) seem in the transition region.

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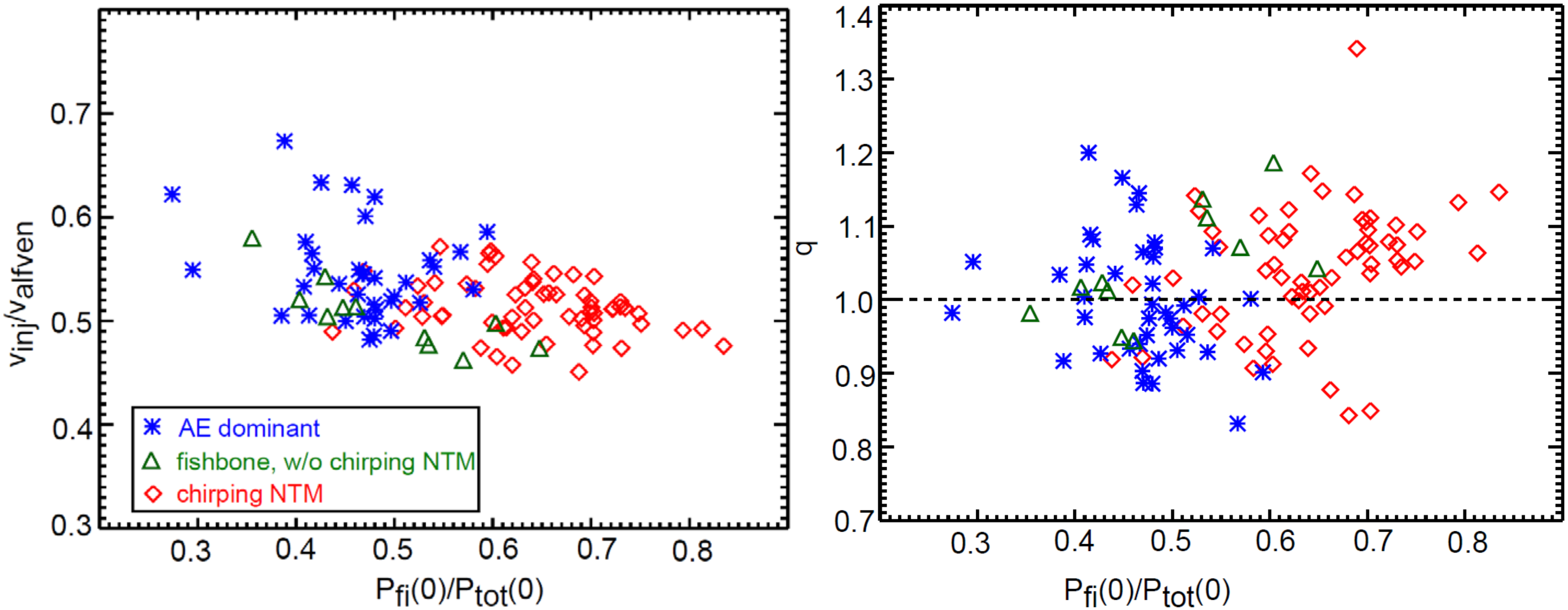

- AE: $P_{fi}(0)/P_{tot}(0)\sim$ 0.3-0.5 and $v_{inj}/v_{alfven}>0.6$
- Low-frequency bursting modes: $P_{fi}(0)/P_{tot}(0)>0.5$ and $v_{inj}/v_{alfven}<0.6$. Pure fishbones (w/o chirping NTM) seem in the transition region.
- Not well separated by q_0

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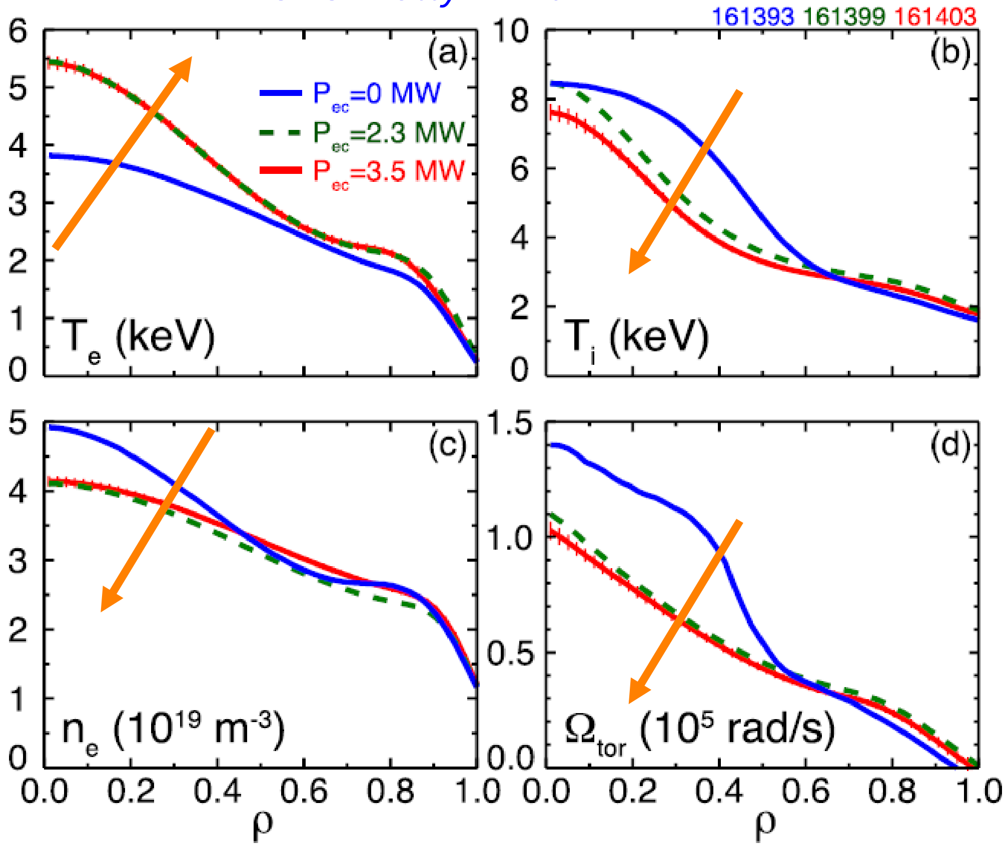
Plasma during ECCD/ECH Always Evolves toward Higher Electron Temperature and Lower Density

C. C. Petty NF 2017



Higher temperature and lower density during EC phase result in an increase of fast-ion slowing-down time

→large (trapped) fast-ion population

→large drive for fishbones

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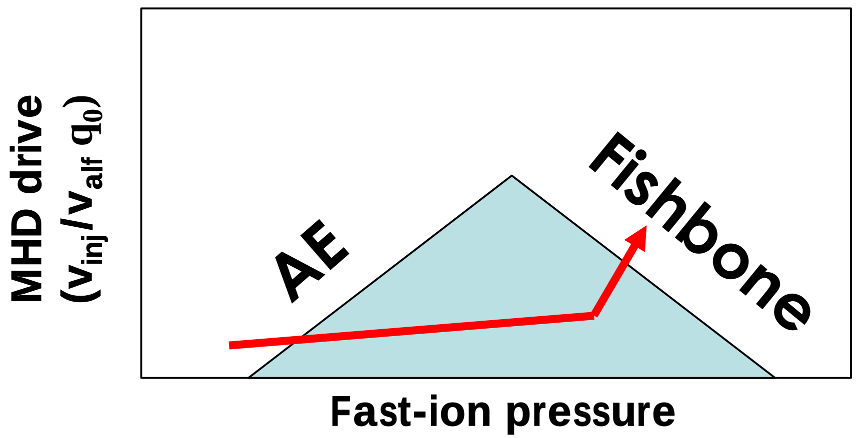
Our Hypotheses for the Transition from AE to Fishbones

- The increase of T_e & decrease in n_e during EC result in a rise of (trapped) fast-ion density, which makes fishbones most unstable.

- The gradual decrease of q_0 also facilitates the excitation of fishbones.



- Although the increase of fast-ion density also increases the drive of AEs, the increase of total plasma pressure and T_e can also increase the damping depending on the AE mode type.

- If unstable first, fast-ion transport induced by the fishbones may relax the gradients that would drive AEs.

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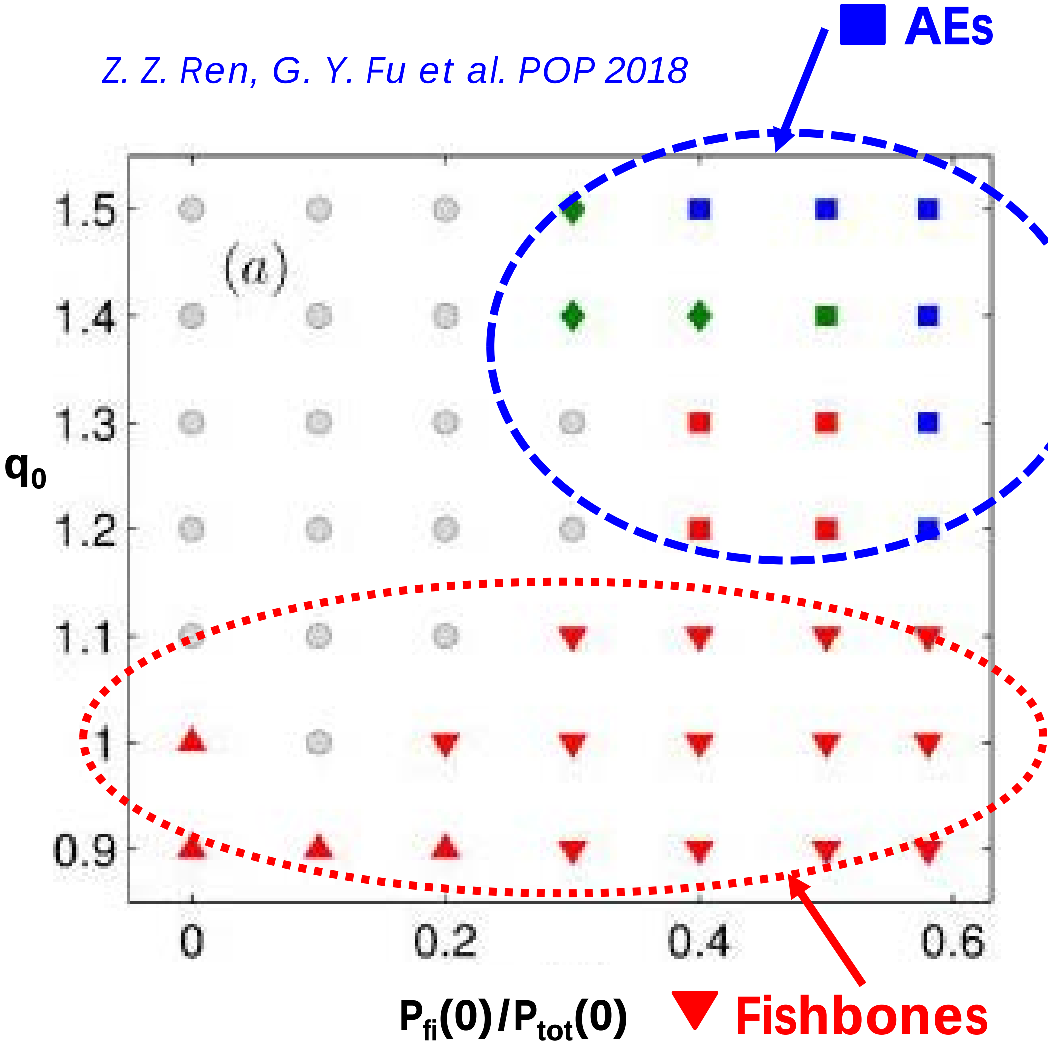
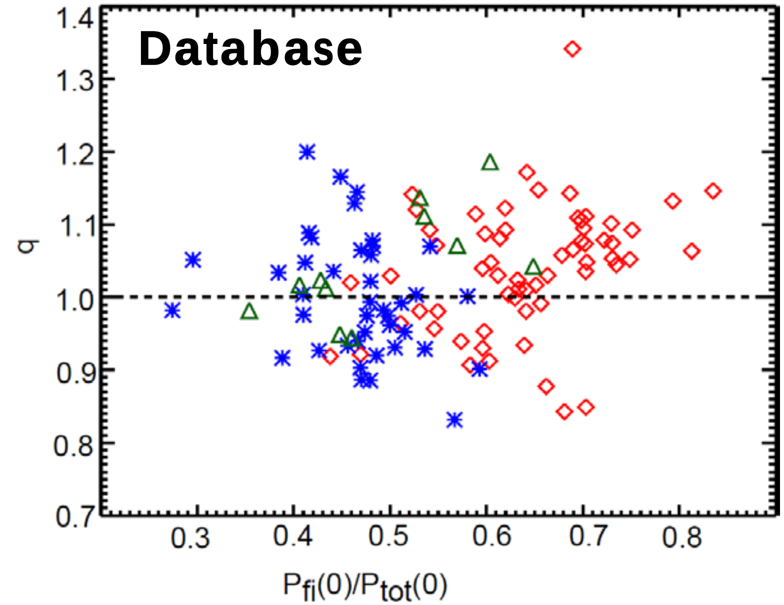
Previous Kinetic/MHD Hybrid Simulations Shows the Transition of AEs to Fishbones could be due to q_0 Drop.

Z. Z. Ren, G. Y. Fu et al. POP 2018



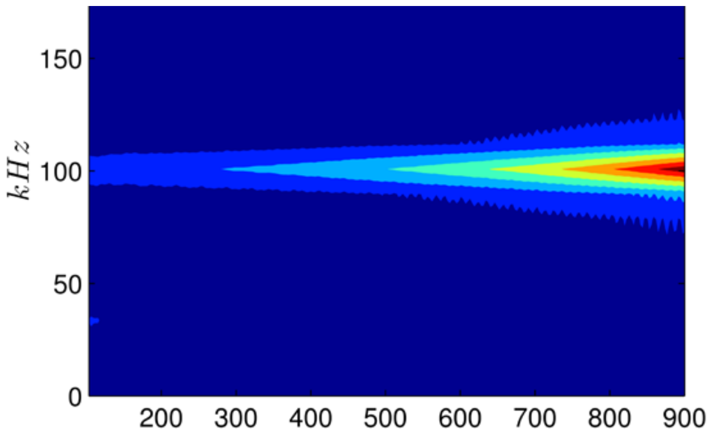


- **This prediction is different from the database observation which suggests the transition from AEs to fishbone is because of large fast-ion population**

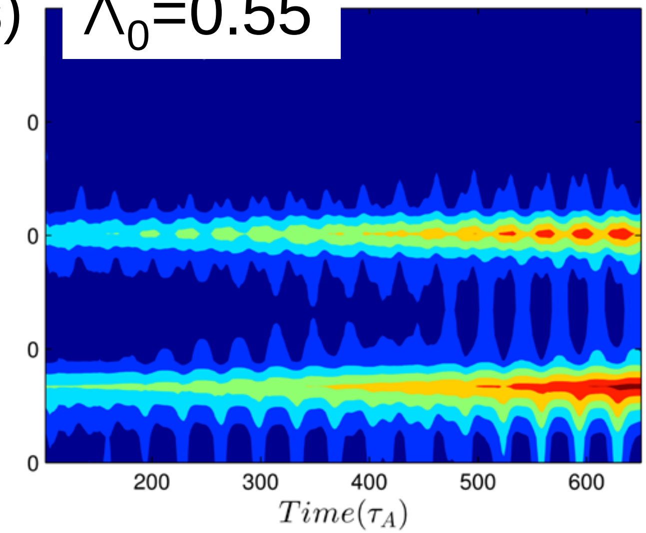
- Note that in the simulations, q_0 and P_{fi}/P_{tot} scan is performed with fixed total pressure and fast ion pitch angle.

Simulations Show that Either AE or Fishbones can be Destabilized Depending on Passing/Trapped Particle Fraction

Λ_0=0.5(more passing ptcls)



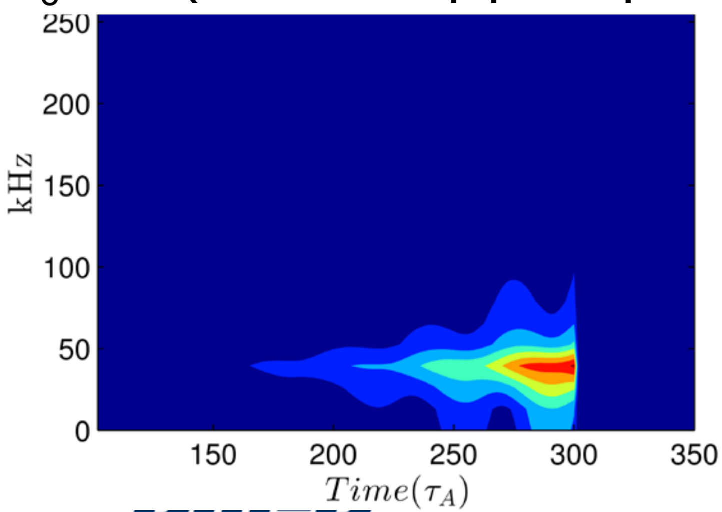
Λ_0=0.55



Kinetic/MHD M3D-K hybrid simulations by Z. Z Ren, G.Y. Fu

$\Lambda_0=\mu B_0/E$

Λ_0=0.6(more trapped ptcls)



Small variation (more trapped particles) of pitch angle in the fast-ion distribution can cause the transition from AE to fishbones.

(Note: tearing mode is not included in the simulations.)

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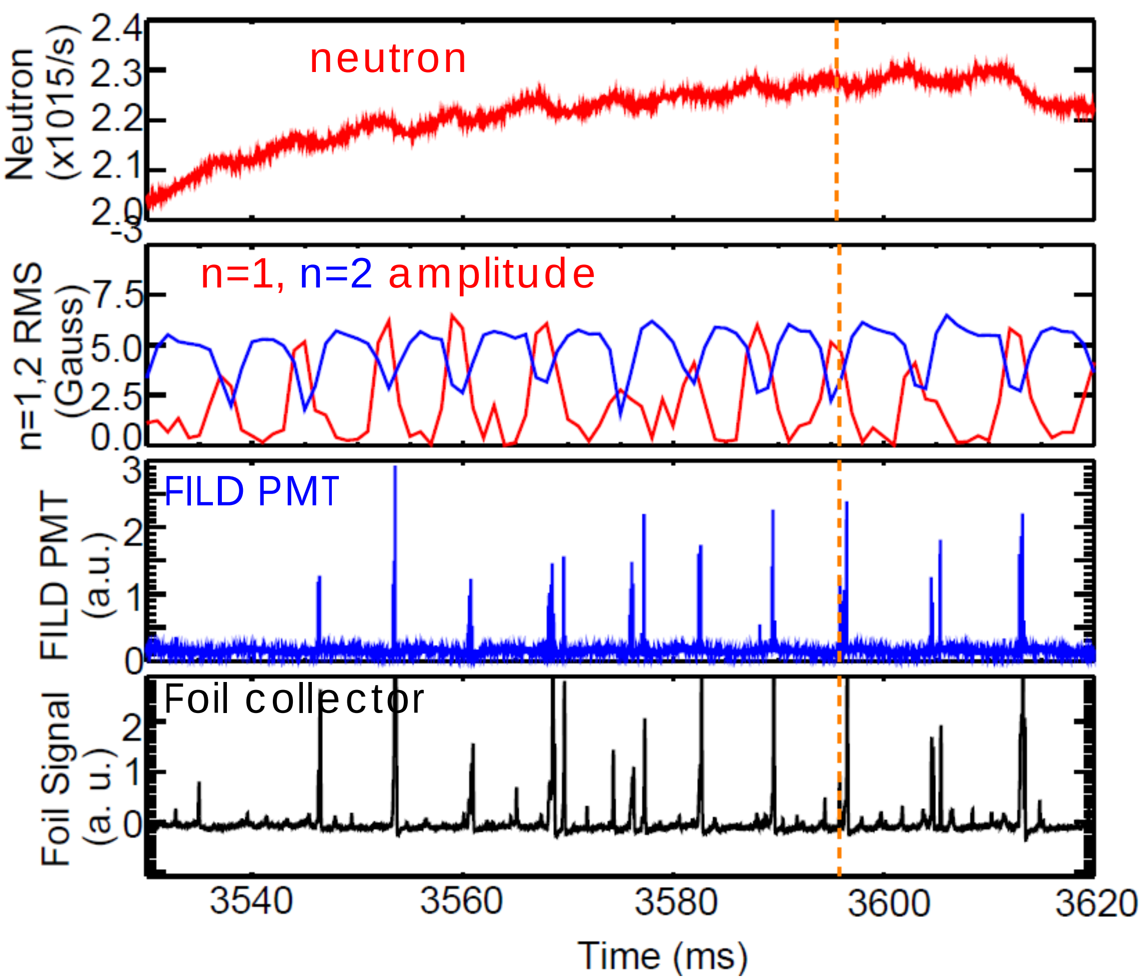
Low-Frequency Busting Mode Sometimes Cause Fast Ion Losses

161410: **chirping NTM** with n=2



- For all **fishbone** cases, fast ion losses are observed in the signals of PMT of FILD system and foil collector. Neutron rate drops 2-3%.
- For **chirping TM** cases, fast ion losses are only observed when the n=1 mode amplitude is large (1/4 of all chirping cases)
- In most chirping NTM cases with relatively weak n=1 mode, no obvious drops in neutron emission; no spikes in fast ion loss and D_a measurements.

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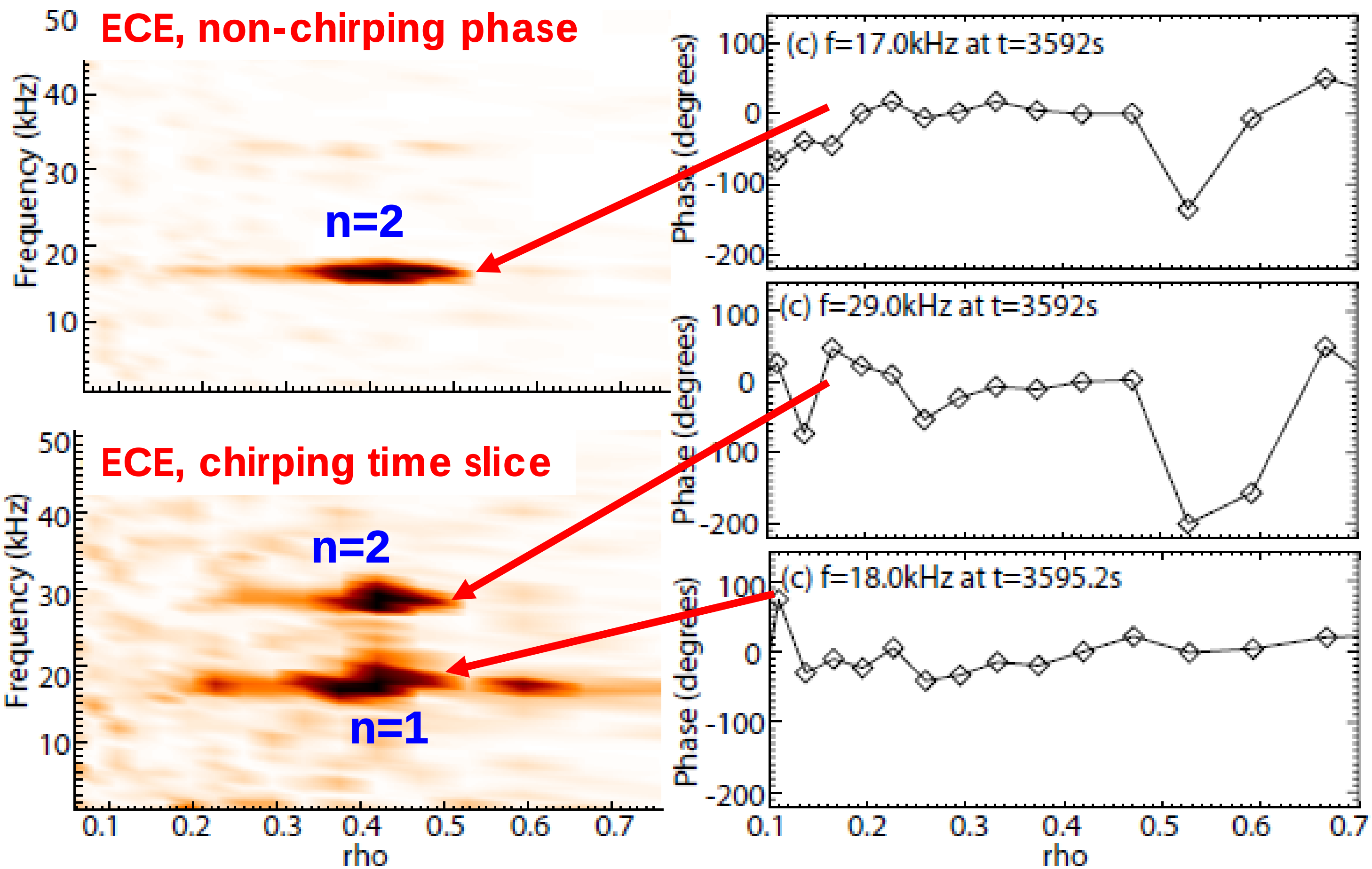
TM is Confirmed by its Phase Variation and Mode Frequency; n=1 Mode has Constant Phase



- The n=2 mode has a 180º phase change near the rational surface.
- n=2 mode frequency is close to the rotation frequency at the rational surface.

Overlapping of Resonance Conditions may Cause Mode Coupling between TM and Fishbones

Wave-particle resonance condition:

wave mode #s

Drift harmonic

$$\omega - n\omega_{\zeta} + (m+l)\omega_{\theta} = 0$$

toroidal transit freq

poloidal transit freq

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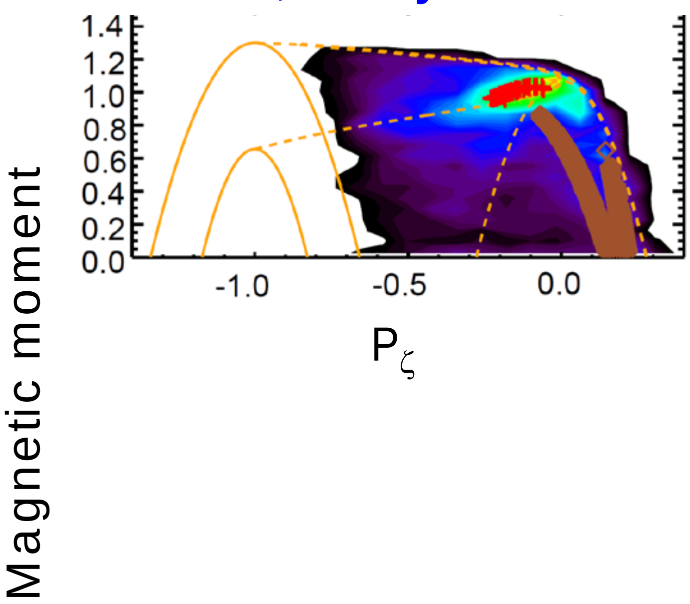
wave mode #s (n, m); Drift harmonic (l); toroidal transit freq (ω_ζ); poloidal transit freq (ω_θ)

E=30keV, **steady NTM** f=18kHz



Symbols: possible orbits that can resonant with fishbones or TM.

p=m+l=0

p=m+l=1

p=m+l=2

Contour: classical fast-ion distribution from TRANSP.

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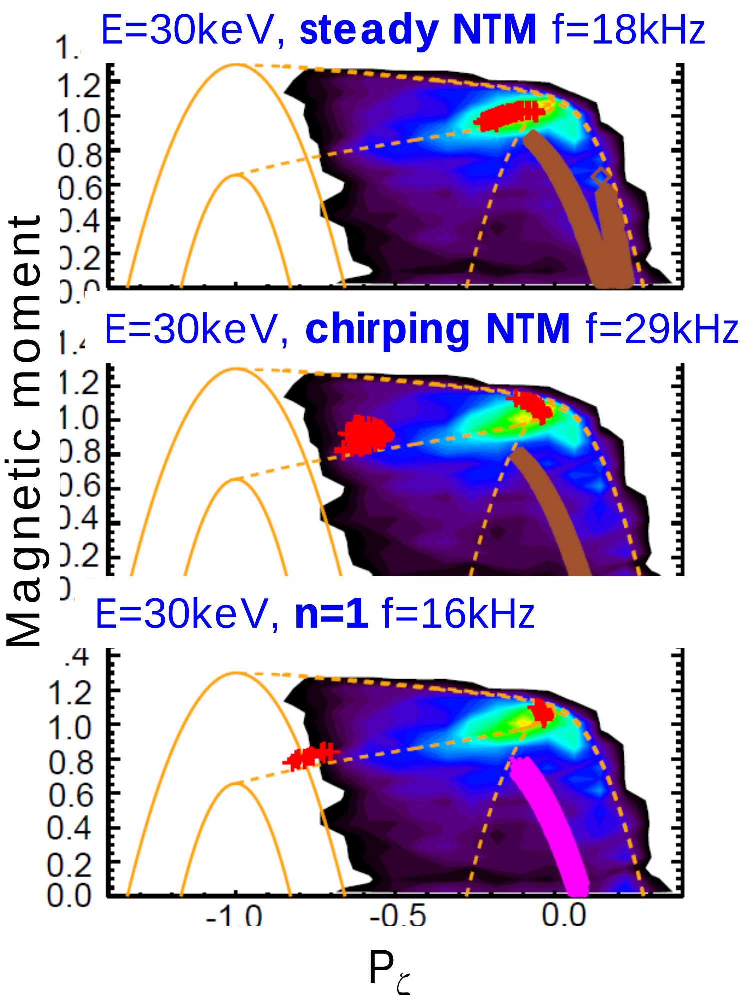

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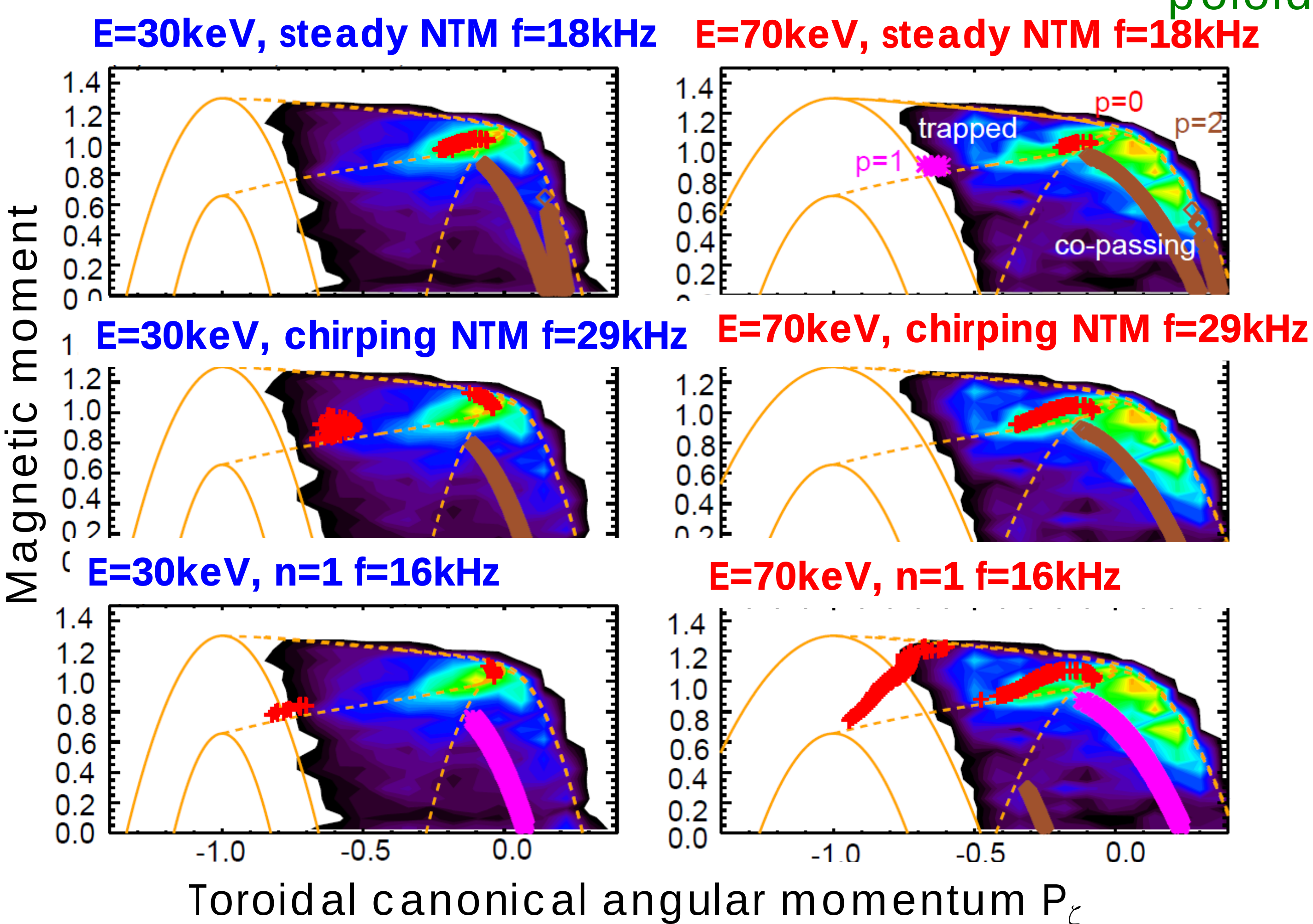

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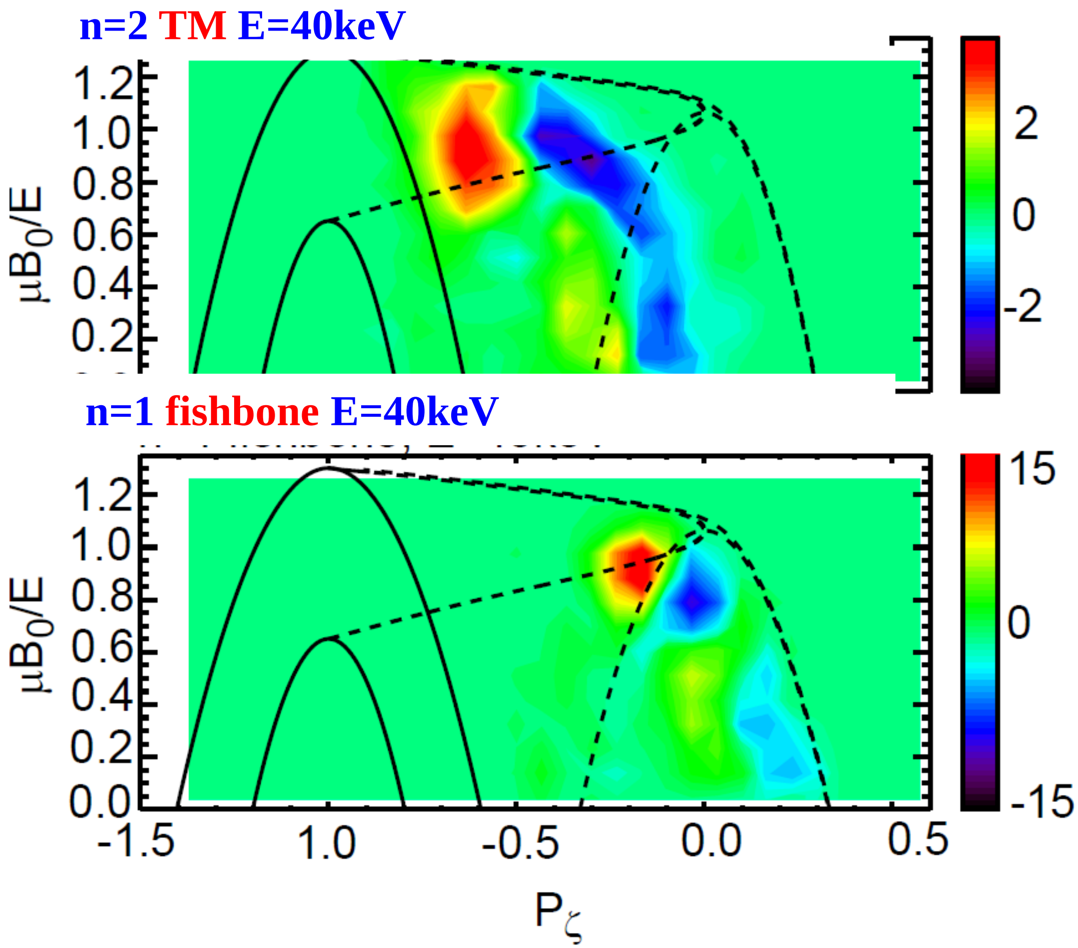
"Kick" Model* Simulations Suggest that n=2 TM and n=1 Fishbone can Interplay through Fast-ion Channeling in Phase-Space

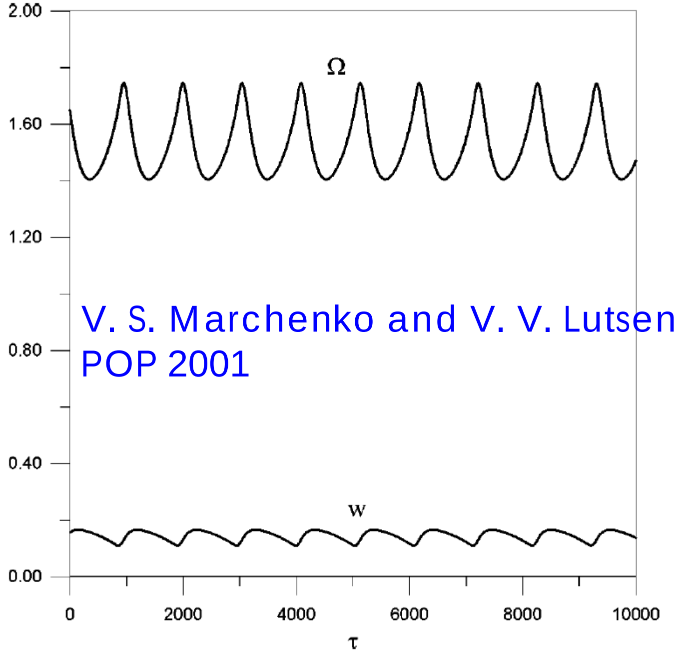
Power flowing from fast ions to fishbone or TM



The resonance of trapped fast ions with TM can weaken the drive for fishbones.

*"Kick" model see M. Podesta's talk I-11 on Thursday

Plausible Reasons for the NTM Island Width Modulation and Frequency Chirping



V. S. Marchenko and V. V. Lutsenko
POP 2001

- **Theory I: resonance with precessing trapped particles** → change fast-ion deposition rate in the resonance region → generate a toroidal torque to accelerate island
- The resonant torque modulates the NTM frequency and amplitude through the **polarization current term**

n_f/n_i

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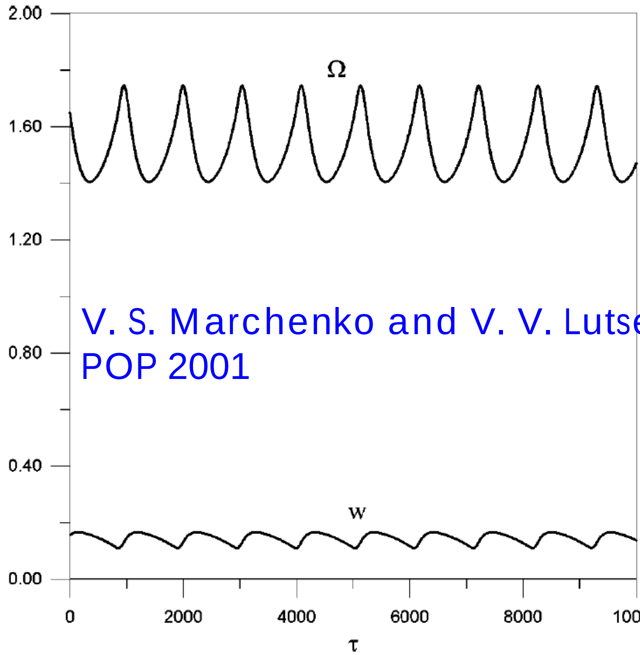

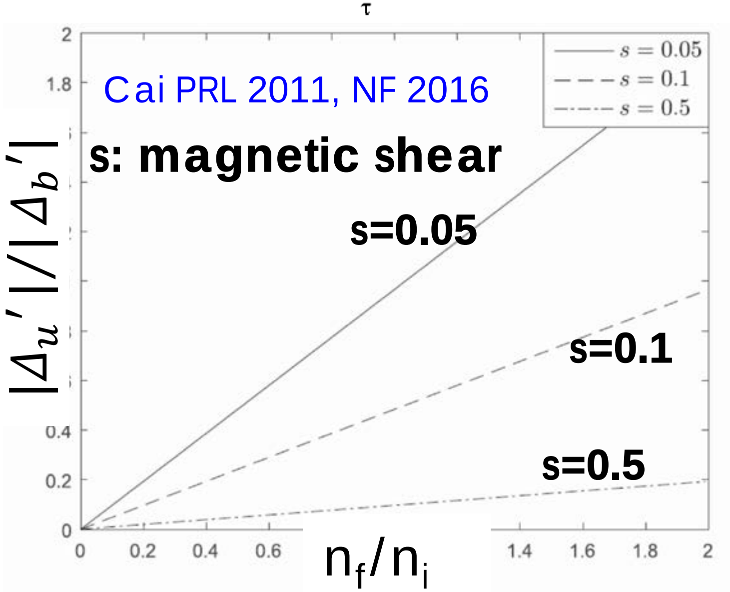

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- **Theory II: extra fast ion contribution term in the modified Rutherford equation**

$$\frac{8\pi}{\eta c^2} I_1 \frac{dw}{dt} = \Delta' + \Delta_b' + \Delta_i' + \Delta_u',$$

$$\Delta_u' = -G_3\left(\frac{r}{sL_n}\right)^2 \frac{\beta_\theta}{w}\frac{\omega'}{\omega_{*i}}\frac{n_h}{n_i}\frac{L_n}{L_h}$$

  - This effect depends on TM propagation freq, magnetic share and fast-ion density gradient.
  - The effect is more significant with weak magnetic shear & high fast-ion density. It may suppress NTM under certain conditions.

Summary and Future Work

- **Observations and database study**
  - With NBI+EC, AE activity is suppressed & replaced by low-f chirping mode
  - The database suggests: (i) low-f chirping modes occur when $P_{fi}(0)/P_{tot}(0)>0.5$ (ii) The q profile change plays a weaker role.
  - Low-f chirping mode is often chirping NTM and occasionally fishbones.
  - Chirping NTMs do not always cause significant fast ion losses. Only when n=1 amplitude is large, small neutron drop(2-3%) & fast ion losses are observed.
- **Modelling**
  - Simulations suggest that increase of trapped fast ions can cause the transition from AE to low-frequency mode.
  - Resonance conditions and "kick" model simulations show that TM and fishbone can interplay through fast-ion channeling in phase space.
  - Island width & frequency modulation may be explained by (1) resonance of TM with trapped particles, (2)cross-field current by resonant fast ions
- **Future work:** (1)self-consistent simulations include fast ions, NTM and fishbones. (2)measurements of response fast ions in phase space (passing vs trapped); island rotation direction and frequency evolution;...

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